Leveraging a functional approach for easier testing and maintenance of ROS 2 code

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Outline

- Introduction
- ROS 2 Conventional Approach
- Introduction to Functional Programming Principles
- Refactoring using Functional Programming Principles
- Conclusion
Introduction
About Me

- Robotics Engineer on the services team at PickNik Robotics
  - Contributed to a wide variety of client projects: remotely operated underwater inspection vehicles, autonomous mobile base for agriculture applications, and more
- Have worked at General Dynamics Electric Boat, MIT Lincoln Laboratory
- Interested in robotics since high school
Why give this talk?

- Engineers at PickNik experiment with different ways to architect code that uses ROS 2 - creating code that is easy to understand, test, maintain, and extend
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- How can the client expect proper operation of the software once they start developing on top of it?
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Answer: Tests and documentation! *Lots and lots of documentation!*
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  - Flaky tests: tests that return both passes and failures despite no changes to the code or the test itself
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- ROS 2 documentation encourages an object-oriented paradigm that can lead to trouble writing code that achieves the goal
- **Adopting functional programming techniques into our code has made it easier to test, maintain, and extend code!**
Motivating Example

- Problem: A robot wants to navigate from its current location to some goal

Clip from https://www.youtube.com/watch?v=VTey-l-Xh6c
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Motivating Example

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- Let’s use an occupancy map to represent the environment
- Assumption: The robot knows its location in the occupancy map at all times

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Motivating Example

- Problem: A robot wants to navigate from its current location to some goal
- The robot needs to know where obstacles are located in its environment
- Let’s use an occupancy map to represent the environment
- Assumption: The robot knows its location in the occupancy map at all times
- Solution: The robot will send a request to a ROS 2 service that generates a path from the robot’s current location and goal location, given an occupancy map

Clip from https://www.youtube.com/watch?v=VTeY-I-Xh6c
ROS 2 Conventional Approach
Conventional Approach

Class PathGenerator:

```cpp
class PathGenerator : public rclcpp::Node {
public:
  explicit PathGenerator(rclcpp::NodeOptions const& options = rclcpp::NodeOptions{}) : Node("path_generator", options) {
    ...
private:
  void set_map_service(const std::shared_ptr<SetMap::Request> request, std::shared_ptr<SetMap::Response> response);
  void generate_path_service(const std::shared_ptr<GetPath::Request> request, std::shared_ptr<GetPath::Response> response);
  bool set_costmap(const std_msgs::msg::UInt8MultiArray& costmap);
  Path generate_global_path(Position const& start, Position const& goal);

  Map<unsigned char> map_; 
  int robot_size_; 
  std::unique_ptr<CollisionChecker<unsigned char>> is_occupied_; 
  rclcpp::Service<SetMap>::SharedPtr map_setter_service_; 
  rclcpp::Service<GetPath>::SharedPtr path_generator_service_; 
};
```

- PathGenerator will be used to generate the path for our robot
- This code was written using example code available from the ROS 2 documentation
- Testing this class requires spinning up clients to send requests to the services and inspecting the responses
Conventional Approach

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class PathGenerator : public rclcpp::Node {
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    bool set_costmap(const std_msgs::msg::UInt8MultiArray& costmap);

    Path generate_global_path(Position const& start, Position const& goal);

    Map<unsigned char> map_;  
    int robot_size_;          
    std::unique_ptr<CollisionChecker<unsigned char>> is_occupied_;  
    rclcpp::Service<SetMap>::SharedPtr map_setter_service_;  
    rclcpp::Service<GetPath>::SharedPtr path_generator_service_;  
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- Is there a way to refactor this code such that invoking the ROS 2 API is avoided?
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- Is there a way to refactor this code such that invoking the ROS 2 API is avoided?
- Yes, by using functional programming principles
Introduction to Functional Programming Principles
What is Functional Programming?

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  - Want to maximize use of these features to write code with a minimal number of side effects
- Let’s go over some principles and see how we can use them in refactoring PathGenerator
Pure Functions

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  - is deterministic: They always return the same output for the same set of inputs
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- A function is pure if and only if it could be replaced by a lookup table (potentially infinitely large!)
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● The Standard Template Library contains many higher order functions!
  ○ std::transform, std::find_if, std::copy, and more
Monadic Error Handling

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  - Type encapsulation: Monadic error handling encapsulates the result of computations along with possible errors within a single type.
  - Compositional error handling: Monadic error handling allows composition of operations that might fail, in a way that if any operation fails, the whole computation fails.
  - Error Propagation: Errors can be automatically propagated through a sequence of computations until they are explicitly handled.
How does functional programming help?

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- Let’s try and refactor PathGenerator
  - Claim: that the refactored PathGenerator has 100% coverage
Refactoring using Functional Programming Principles
Refactoring PathGenerator

### How the current PathGenerator looks

```cpp
class PathGenerator : public rclcpp::Node {
public:
  explicit PathGenerator(rclcpp::NodeOptions const& options = rclcpp::NodeOptions{}): Node("path_generator", options) {
private:
  void set_map_service(const std::shared_ptr<SetMap::Request> request, std::shared_ptr<SetMap::Response> response);
  void generate_path_service(const std::shared_ptr<GetPath::Request> request, std::shared_ptr<GetPath::Response> response);
  bool set_costmap(const std_msgs::msg::UInt8MultiArray& costmap);
  Path generate_global_path(Position const& start, Position const& goal);
/* Additional private members*/
};
```
A `rclcpp::Node` object can be constructed in main and services can be assigned.

No need to have a `PathGenerator` object that inherits from `rclcpp::Node`.

```cpp
class PathGenerator : public rclcpp::Node {

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- A `rclcpp::Node` object can be constructed in main and services can be assigned
- No need to have a `PathGenerator` object that inherits from `rclcpp::Node`
- The `create_service` method accepts class methods, free functions, and lambdas as the callback function
- The private functions of `PathGenerator` can be turned into free functions and lambda functions
A `rclcpp::Node` object can be constructed in main and services can be assigned.
- No need to have a `PathGenerator` object that inherits from `rclcpp::Node`.
- The `create_service` method accepts class methods, free functions, and lambdas as the callback function.
- The private functions of `PathGenerator` can be turned into free functions and lambda functions.
- Let’s refactor the callback function for the `generate path` service.

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};
```
void generate_path_service(
const std::shared_ptr<GetPath::Request> request,
  std::shared_ptr<GetPath::Response> response) {
if (map_.get_data().size() == 0) {
  RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
  response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
  response->path = std_msgs::msg::UInt8MultiArray();
  return;
} /* More error pre-checks */

auto const start = Position{request->start.data[0], request->start.data[1]};
auto const goal = Position{request->goal.data[0], request->goal.data[1]};

// Generate the path
auto const path = generate_global_path(start, goal);

// Start populating the response message
auto response_path = std_msgs::msg::UInt8MultiArray();

/* Code about populating the message here */

response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS :
example_srvs::msg::GetPathCodes::NO_VALID_PATH;
  response->path = response_path;
}
void generate_path_service(
    const std::shared_ptr<GetPath::Request> request,
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    auto const start = Position{request->start.data[0], request->start.data[1]};
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- `generate_path_service` is:
  - printing errors
  - generating the path
Refactoring PathGenerator

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generate_path_service is:

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Refactoring PathGenerator

- generate_path_service is:
  - printing errors
  - generating the path
  - setting an out parameter
- Let's isolate the error printing functionality to another function
  - The error printing function needs to be passed an error type

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  auto const path = generate_global_path(start, goal);
  /* Start populating the response message */
  auto response_path = std_msgs::msg::UInt8MultiArray();
  /* Code about populating the message here */
  response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS : example_srvs::msg::GetPathCodes::NO_VALID_PATH;
  response->path = response_path;
}
```
Refactoring PathGenerator

void generate_path_service(const std::shared_ptr<GetPath::Request> request, const std::shared_ptr<GetPath::Response> response) {
if (map_.get_data().size() == 0) {
  RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
  response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
  response->path = std_msgs::msg::UInt8MultiArray();
  return;
}
/* More error pre-checks */

auto const start = Position{request->start.data[0], request->start.data[1]};
auto const goal = Position{request->goal.data[0], request->goal.data[1]};

// Generate the path
auto const path = generate_global_path(start, goal);

// Start populating the response message
auto response_path = std_msgs::msg::UInt8MultiArray();

/* Code about populating the message here */

response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS :
example_srvs::msg::GetPathCodes::NO_VALID_PATH;
  response->path = response_path;
}
Refactoring PathGenerator

void generate_path_service(
    const std::shared_ptr<GetPath::Request> request,
    std::shared_ptr<GetPath::Response> response) {
    if (map_.get_data().size() == 0) {
        RCLCPP_ERROR_STREAM(this->get_logger(), "MAP IS EMPTY!!");
        response->code.code = example_srvs::msg::GetPathCodes::EMPTY_OCCUPANCY_MAP;
        response->path = std_msgs::msg::UInt8MultiArray();
        return;
    }
    /* More error pre-checks */

    auto const start = Position{request->start.data[0], request->start.data[1]};
    auto const goal = Position{request->goal.data[0], request->goal.data[1]};

    // Generate the path
    auto const path = generate_global_path(start, goal);

    // Start populating the response message
    auto response_path = std_msgs::msg::UInt8MultiArray();

    /* Code about populating the message here */

    response->code.code = !path.empty() ? example_srvs::msg::GetPathCodes::SUCCESS :
        example_srvs::msg::GetPathCodes::NO_VALID_PATH;
    response->path = response_path;
}
Refactoring PathGenerator

std::expected<GetPath::Response, error> generate_path(
  std::shared_ptr<GetPath::Request> const request,
  Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
  if (occupancy_map.get_data().size() == 0) {
    return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
  }
  /* More error pre-checks */
  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path using the path generator function that was input
  auto const path = path_generator(start, goal, occupancy_map);
  if (!path.has_value()) {
    return std::unexpected(error::NO_VALID_PATH);
  }
  auto response = GetPath::Response{};
  /* More implementation code */
  return response;
}
Refactoring PathGenerator

```cpp
std::expected<GetPath::Response, error> generate_path(
    std::shared_ptr<GetPath::Request> const request,
    Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
    if (occupancy_map.get_data().size() == 0) {
        return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
    }
    /* More error pre-checks */

    auto const start = Position{request->start.data[0], request->start.data[1]};
    auto const goal = Position{request->goal.data[0], request->goal.data[1]};

    // Generate the path using the path generator function that was input
    auto const path = path_generator(start, goal, occupancy_map);
    if (!path.has_value()) {
        return std::unexpected(error::NO_VALID_PATH);
    }

    auto response = GetPath::Response{};
    /* More implementation code */
    return response;
}
```

- Here is the refactored core functionality of the generate path callback
- This function returns a type which can be used for monadic error handling
std::expected<GetPath::Response, error> generate_path(
  std::shared_ptr<GetPath::Request> const request,
  Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
  if (occupancy_map.get_data().size() == 0) {
    return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
  }
/* More error pre-checks */

  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path using the path generator function that was input
  auto const path = path_generator(start, goal, occupancy_map);
  if (!path.has_value()) {
    return std::unexpected(error::NO_VALID_PATH);
  }

  auto response = GetPath::Response{};
/* More implementation code */
  return response;
}
Refactoring PathGenerator

Here is the refactored core functionality of the generate path callback:

- This function returns a type which can be used for monadic error handling.
- If there is an error, the function can handle the error in a compile time checkable way.
- The function that generates the path can now be passed in, making this function a higher order function.

```cpp
using PathingGenerator = std::function<std::optional<Path>(
    Position const&, Position const&, Map<unsigned char> const&)>;

std::expected<GetPath::Response, error> generate_path(
    std::shared_ptr<GetPath::Request> const request, 
    Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
    if (occupancy_map.get_data().size() == 0) {
        return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
    }
    /* More error pre-checks */
    auto const start = Position{request->start.data[0], request->start.data[1]};
    auto const goal = Position{request->goal.data[0], request->goal.data[1]};

    // Generate the path using the path generator function that was input
    auto const path = path_generator(start, goal, occupancy_map);
    if (!path.has_value()) {
        return std::unexpected(error::NO_VALID_PATH);
    }
    auto response = GetPath::Response{};
    /* More implementation code */
    return response;
}
```
Refactoring PathGenerator

Using PathingGenerator = std::function<std::optional<Path>(
    Position const&, Position const&, Map<unsigned char> const&>>;

std::expected<GetPath::Response, error> generate_path(
    std::shared_ptr<GetPath::Request> const request,
    Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
  if (occupancy_map.get_data().size() == 0) {
    return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
  }
  /* More error pre-checks */

  auto const start = Position{request->start.data[0], request->start.data[1]};
  auto const goal = Position{request->goal.data[0], request->goal.data[1]};

  // Generate the path using the path generator function that was input
  auto const path = path_generator(start, goal, occupancy_map);
  if (!path.has_value()) {
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  /* More implementation code */
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Refactoring PathGenerator

using PathingGenerator = std::function<std::optional<Path>(
    Position const&, Position const&, Map<unsigned char> const&)>;

std::expected<GetPath::Response, error> generate_path(
    std::shared_ptr<GetPath::Request> const request,
    Map<unsigned char> const& occupancy_map, PathingGenerator path_generator) {
    if (occupancy_map.get_data().size() == 0) {
        return std::unexpected(error::EMPTY_OCCUPANCY_MAP);
    }
    /* More error pre-checks */
    auto const start = Position{request->start.data[0], request->start.data[1]};
    auto const goal = Position{request->goal.data[0], request->goal.data[1]};

    // Generate the path using the path generator function that was input
    auto const path = path_generator(start, goal, occupancy_map);
    if (!path.has_value()) {
        return std::unexpected(error::NO_VALID_PATH);
    }

    auto response = GetPath::Response{};
    /* More implementation code */
    return response;
}
Testing the Refactored PathGenerator

TEST(GeneratePath, NoValidPath) {
  // GIVEN a GetPath request and an occupancy map
  auto const sample_occupancy_map = get_test_occupancy_map();

  auto const request = std::make_shared<GetPath::Request>();

  request->start.data = {2, 2};
  request->goal.data = {5, 5};

  // WHEN the path is requested
  auto const response = pathing::generate_path::generate_path(
      request, sample_occupancy_map, pathing::generate_global_path);

  // THEN there should be an error with the error::NO_VALID_PATH type
  EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}
Testing the Refactored PathGenerator

TEST(GeneratePath, NoValidPath) {
    // GIVEN a GetPath request and an occupancy map
    auto const sample_occupancy_map = get_test_occupancy_map();

    auto const request = std::make_shared<GetPath::Request>();

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    EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}

• Testing the refactored functionality is trivial
Testing the Refactored PathGenerator

- Testing the refactored functionality is trivial
  - Create required parameters

```cpp
TEST(GeneratePath, NoValidPath) {
    // GIVEN a GetPath request and an occupancy map
    auto const sample_occupancy_map = get_test_occupancy_map();
    auto const request = std::make_shared<GetPath::Request>();
    request->start.data = {2, 2};
    request->goal.data = {5, 5};

    // WHEN the path is requested
    auto const response = pathing::generate_path::generate_path(
        request, sample_occupancy_map, pathing::generate_global_path);

    // THEN there should be an error with the error::NO_VALID_PATH type
    EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}
```
Testing the Refactored PathGenerator

TEST(GeneratePath, NoValidPath) {
    // GIVEN a GetPath request and an occupancy map
    auto const sample_occupancy_map = get_test_occupancy_map();

    auto const request = std::make_shared<GetPath::Request>();
    request->start.data = {2, 2};
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    // WHEN the path is requested
    auto const response = pathing::generate_path::generate_path(
        request, sample_occupancy_map, pathing::generate_global_path);

    // THEN there should be an error with the error::NO_VALID_PATH type
    EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}

- Testing the refactored functionality is trivial
  ○ Create required parameters
  ○ Pass the parameters into the function under test
Testing the Refactored PathGenerator

Testing the refactored functionality is trivial
  ○ Create required parameters
  ○ Pass the parameters into the function under test
  ○ Check the return

```cpp
TEST(GeneratePath, NoValidPath) {
  // GIVEN a GetPath request and an occupancy map
  auto const sample_occupancy_map = get_test_occupancy_map();

  auto const request = std::make_shared<GetPath::Request>();
  request->start.data = {2, 2};
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  // WHEN the path is requested
  auto const response = pathing::generate_path::generate_path(
    request, sample_occupancy_map, pathing::generate_global_path);

  // THEN there should be an error with the error::NO_VALID_PATH type
  EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}
```
Testing the Refactored PathGenerator

Testing the refactored functionality is trivial
○ Create required parameters
○ Pass the parameters into the function under test
○ Check the return

All the functions that have been refactored so far can be tested this way
Testing the Refactored PathGenerator

### Testing the refactored functionality is trivial
- Create required parameters
- Pass the parameters into the function under test
- Check the return

### All the functions that have been refactored so far can be tested this way

### Everything can now be put together for the callback being executed by the generate path service

```cpp
TEST(GeneratePath, NoValidPath) {
  // GIVEN a GetPath request and an occupancy map
  auto const sample_occupancy_map = get_test_occupancy_map();

  auto const request = std::make_shared<GetPath::Request>();

  request->start.data = {2, 2};
  request->goal.data = {5, 5};

  // WHEN the path is requested
  auto const response = pathing::generate_path::generate_path(
    request, sample_occupancy_map, pathing::generate_global_path);

  // THEN there should be an error with the error::NO_VALID_PATH type
  EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}
```
Testing the Refactored PathGenerator

TEST(GeneratePath, NoValidPath) {
   // GIVEN a GetPath request and an occupancy map
   auto const sample_occupancy_map = get_test_occupancy_map();

   auto const request = std::make_shared<GetPath::Request>();

   request->start.data = {2, 2};
   request->goal.data = {5, 5};

   // WHEN the path is requested
   auto const response = pathing::generate_path::generate_path(
      request, sample_occupancy_map, pathing::generate_global_path);

   // THEN there should be an error with the error::NO_VALID_PATH type
   EXPECT_EQ(response.error(), pathing::generate_path::error::NO_VALID_PATH);
}

● Testing the refactored functionality is trivial
  ○ Create required parameters
  ○ Pass the parameters into the function under test
  ○ Check the return

● All the functions that have been refactored so far can be tested this way

● Everything can now be put together for the callback being executed by the generate path service

● All of this has been done without invoking the ROS 2 API!
Putting it all together

```cpp
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const return_empty_response = []([[maybe_unused]] auto const)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const stringify_error = [](auto const error) {...};

    *response = generate_path::generate_path(request, this->map_,
        generate_global_path)
        .map_error(stringify_error)
        .or_else(print_error)
        .or_else(return_empty_response)
        .value();
}
```

- The generate path callback function has been replaced by a lambda function
Putting it all together

```cpp
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const return_empty_response = []([[maybe_unused]] auto const)
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    auto const stringify_error = [](auto const error) {...};

    *response = generate_path::generate_path(request, this->map_,
        generate_global_path)
        .map_error(stringify_error)
        .or_else(print_error)
        .or_else(return_empty_response)
        .value();
}
```

- The generate path callback function has been replaced by a lambda function.
- If `generate_path` returns the expected value, it is directly assigned to `response`.

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Putting it all together

```cpp
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error) -> std::expected<GetPath::Response, std::string> {...};
    auto const return_empty_response = []([[maybe_unused]] auto const) -> std::expected<GetPath::Response, std::string> {...};
    auto const stringify_error = [](auto const error) {...};
    *response = generate_path::generate_path(request, this->map_, generate_global_path)
        .map_error(stringify_error)
        .or_else(print_error)
        .or_else(return_empty_response)
        .value();
}
```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`
- If `generate_path` returns an error, the error is handled by chaining functions together
  - This is the result of returning a monadic type and performing monadic error handling
Putting it all together

```cpp
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error)
        -> std::expected<GetPath::Response, std::string> {...};
    auto const return_empty_response = []([[maybe_unused]] auto const)
        -> std::expected<GetPath::Response, std::string> {...};
    auto const stringify_error = [](auto const error) {...};
    *response = generate_path::generate_path(request, this->map_,
        generate_global_path)
        .map_error(stringify_error)
        .or_else(print_error)
        .or_else(return_empty_response)
        .value();
}
```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`
- If `generate_path` returns an error, the error is handled by chaining functions together
  - This is the result of returning a monadic type and performing monadic error handling
- If needed, more functions can be added to manipulate the expected type or error type, increasing modularity
Putting it all together

```cpp
[this](auto const request, auto response) {
    auto const print_error = [this](std::string_view error)
        -> std::expected<GetPath::Response, std::string> {...};

    auto const return_empty_response = [](){[[maybe_unused]] auto const}
        -> std::expected<GetPath::Response, std::string> {...};

    auto const stringify_error = [](auto const error) {...};

    *response = generate_path::generate_path(request, this->map_,
        generate_global_path)
        .map_error(stringify_error)
        .or_else(print_error)
        .or_else(return_empty_response)
        .value();
}
```

- The generate path callback function has been replaced by a lambda function
- If `generate_path` returns the expected value, it is directly assigned to `response`
- If `generate_path` returns an error, the error is handled by chaining functions together
  - This is the result of returning a monadic type and performing monadic error handling
- If needed, more functions can be added to manipulate the expected type or error type, increasing modularity
- How can this lambda be tested?
DI and Functional Programming

- With Dependency Injection (DI)!

```cpp
template <typename ServiceType>
using ServiceCallback = std::function<void(
    std::shared_ptr<typename ServiceType::Request> const ,
    std::shared_ptr<typename ServiceType::Response>)));

struct Manager {
    struct MiddlewareHandle {
        // Define map service callback type
        using SetMapCallback = ServiceCallback<SetMap>;
        // Define path generation service callback type
        using GeneratePathCallback = ServiceCallback<GetPath>;

        virtual ~MiddlewareHandle() = default;

        virtual void register_set_map_service(SetMapCallback callback) = 0;
        virtual void register_generate_path_service(GeneratePathCallback callback) = 0;
        virtual void log_error(std::string const& msg) = 0;
        virtual void log_info(std::string const& msg) = 0;
    };

    Manager(std::unique_ptr<MiddlewareHandle> mw);

    private:
    std::unique_ptr<MiddlewareHandle> mw_;
    Map<unsigned char> map_;
};
```
DI and Functional Programming

- With Dependency Injection (DI)!
  - DI is used to move or “inject” objects into another object

```cpp
template <typename ServiceType>
using ServiceCallback = std::function<void(
    std::shared_ptr<typename ServiceType::Request> const ,
    std::shared_ptr<typename ServiceType::Response>)>;

struct Manager {
    struct MiddlewareHandle {
        // Define map service callback type
        using SetMapCallback = ServiceCallback<SetMap>;

        // Define path generation service callback type
        using GeneratePathCallback = ServiceCallback<GetPath>;

        virtual ~MiddlewareHandle() = default;

        virtual void register_set_map_service(SetMapCallback callback) = 0;

        virtual void register_generate_path_service(GeneratePathCallback callback) = 0;

        virtual void log_error(std::string const& msg) = 0;

        virtual void log_info(std::string const& msg) = 0;
    };

    Manager(std::unique_ptr<MiddlewareHandle> mw);

    private:
        std::unique_ptr<MiddlewareHandle> mw_;

        Map<unsigned char> map_;
};
```
DI and Functional Programming

`template<typename ServiceType>
using ServiceCallback = std::function<void(
    std::shared_ptr<typename ServiceType::Request>const,
    std::shared_ptr<typename ServiceType::Response>));`

```cpp
struct Manager {
    struct MiddlewareHandle {
        // Define map service callback type
        using SetMapCallback = ServiceCallback<SetMap>;

        // Define path generation service callback type
        using GeneratePathCallback = ServiceCallback<GetPath>;

        virtual ~MiddlewareHandle() = default;

        virtual void register_set_map_service(SetMapCallback callback) = 0;

        virtual void register_generate_path_service(GeneratePathCallback callback) = 0;

        virtual void log_error(std::string const& msg) = 0;

        virtual void log_info(std::string const& msg) = 0;
    };

    Manager(std::unique_ptr<MiddlewareHandle> mw);

    private:
    std::unique_ptr<MiddlewareHandle> mw_;

    Map<unsigned char> map_;}
};
```

- With Dependency Injection (DI)!
  - DI is used to move or “inject” objects into another object
- There still needs to be mutable state, to keep track of the occupancy map between service calls, thus the map_ member variable
With Dependency Injection (DI)!

- DI is used to move or “inject” objects into another object
- There still needs to be mutable state, to keep track of the occupancy map between service calls, thus the map_ member variable
- For the Manager object, a MiddlewareHandle struct is defined that is the interface for the injected dependency
- This abstract interface can be used to implement each function using the ROS API
DI and Functional Programming

- With Dependency Injection (DI)!
  - DI is used to move or “inject” objects into another object
- There still needs to be mutable state, to keep track of the occupancy map between service calls, thus the map_ member variable
- For the Manager object, a MiddlewareHandle struct is defined that is the interface for the injected dependency
- This abstract interface can be used to implement each function using the ROS API
- The lambda function that is used for the generate path service can be captured via mocking and tested

```cpp
template <typename ServiceType>
using ServiceCallback = std::function<void(
    std::shared_ptr<typename ServiceType::Request> const ,
    std::shared_ptr<typename ServiceType::Response>))>

struct Manager {
    struct MiddlewareHandle {
        // Define map service callback type
        using SetMapCallback = ServiceCallback<SetMap>;

        // Define path generation service callback type
        using GeneratePathCallback = ServiceCallback<GetPath>;

        virtual ~MiddlewareHandle() = default;

        virtual void register_set_map_service(SetMapCallback callback) = 0;

        virtual void register_generate_path_service(GeneratePathCallback callback) = 0;

        virtual void log_error(std::string const& msg) = 0;

        virtual void log_info(std::string const& msg) = 0;
    }

    Manager(std::unique_ptr<MiddlewareHandle> mw);

private:
    std::unique_ptr<MiddlewareHandle> mw_

    Map<unsigned char> map_;  // Map for occupancy state
};
```
Testing with DI

struct PathManagerFixture : public testing::Test {
    PathManagerFixture() : mw_{std::make_unique<MockMiddlewareHandle>()} {
        // When the map callback is called, set the costmap
        ON_CALL(*mw_, register_set_map_service(testing::_))
            .WillByDefault([&](auto const& map_callback) {
                auto const map_request = make_occupancy_map();
            auto const map_response = std::make_shared<SetMap::Response>();
            map_callback(map_request, map_response);
            });
        // Capture the path callback so it can be called later
        ON_CALL(*mw_, register_generate_path_service(testing::_))
            .WillByDefault(testing::SaveArg<0>(&path_callback_));
    }

    std::unique_ptr<MockMiddlewareHandle> mw_;
    pathing::Manager::MiddlewareHandle::GeneratePathCallback path_callback_;
};

TEST_F(PathManagerFixture, NoPath) {
    // GIVEN a path generator with a costmap
    auto const path_generator = pathing::Manager{std::move(mw_)};
    // WHEN the generate path service is called with an unreachable goal
    auto path_request = std::make_shared<GetPath::Request>();
    path_request->start.data = {2, 2};
    path_request->goal.data = {5, 5};
    auto path_response = std::make_shared<GetPath::Response>();
    path_callback_(path_request, path_response);
    // THEN the path generator should succeed
    EXPECT_EQ(path_response->code.code, example_srvs::msg::GetPathCodes::NO_VALID_PATH);
    auto const expected = pathing::Path{};
    // AND the path should be empty
    EXPECT_EQ(pathing::utilities::parseGeneratedPath(path_response->path), expected);
}
struct PathManagerFixture : public testing::Test {
    PathManagerFixture() : mw_{std::make_unique<MockMiddlewareHandle>()} {
        // When the map callback is called, set the costmap
        ON_CALL(*mw_, register_set_map_service(testing::_)).WillByDefault([&](auto const& map_callback) {
            auto const map_request = make_occupancy_map();
            auto map_response = std::make_shared<SetMap::Response>();
            map_callback(map_request, map_response);
        });
        // Capture the path callback so it can be called later
        ON_CALL(*mw_, register_generate_path_service(testing::_)).WillByDefault(testing::SaveArg<0>(&path_callback_));
    }

    std::unique_ptr<MockMiddlewareHandle> mw_;
    pathing::Manager::MiddlewareHandle::GeneratePathCallback path_callback_;
};

TEST_F(PathManagerFixture, NoPath) {
    // GIVEN a path generator with a costmap
    auto const path_generator = pathing::Manager{std::move(mw_)};
    // WHEN the generate path service is called with an unreachable goal
    auto path_request = std::make_shared<GetPath::Request>();
    path_request->start.data = {2, 2};
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    auto path_response = std::make_shared<GetPath::Response>();
    path_callback_(path_request, path_response);
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    EXPECT_EQ(path_response->code.code, example_srvs::msg::GetPathCodes::NO_VALID_PATH);
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    EXPECT_EQ(pathing::utilities::parseGeneratedPath(path_response->path), expected);
}
struct PathManagerFixture : public testing::Test {
    PathManagerFixture() : mw_(std::make_unique<MockMiddlewareHandle>()) {
        // When the map callback is called, set the costmap
        ON_CALL(*mw_, register_set_map_service(testing::_)).WillByDefault(
            [&](auto const& map_callback) {
                auto const map_request = make_occupancy_map();
                auto map_response = std::make_shared<SetMap::Response>();
                map_callback(map_request, map_response);
            });
        // Capture the path callback so it can be called later
        ON_CALL(*mw_, register_generate_path_service(testing::_)).WillByDefault(
            testing::SaveArg<0>(&path_callback_));
    }

    std::unique_ptr<MockMiddlewareHandle> mw_;
    pathing::Manager::MiddlewareHandle::GeneratePathCallback path_callback_;
}

TEST_F(PathManagerFixture, NoPath) {
    // GIVEN a path generator with a costmap
    auto const path_generator = pathing::Manager{
        std::move(mw_)};
    // WHEN the generate path service is called with an unreachable goal
    auto path_request = std::make_shared<GetPath::Request>();
    path_request->start.data = {2, 2};
    path_request->goal.data = {5, 5};
    auto path_response = std::make_shared<GetPath::Response>();
    path_callback_(path_request, path_response);
    // THEN the path generator should succeed
    EXPECT_EQ(path_response->code.code, example_srvs::msg::GetPathCodes::NO_VALID_PATH);
    auto const expected = pathing::Path{};
    // AND the path should be empty
    EXPECT_EQ(pathing::utilities::parseGeneratedPath(path_response->path), expected);
}

- Here is the code testing the generate path lambda function
- This test fixture calls the callback function for the set occupancy map service when a mock function is executed
- This test fixture also captures the callback function for the generate path service so it can be executed later
struct PathManagerFixture : public testing::Test {
PathManagerFixture() : mw_{std::make_unique<MockMiddlewareHandle>()} {
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Testing with DI

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}
```

- Here is the code testing the generate path lambda function
- This test fixture calls the callback function for the set occupancy map service when a mock function is executed
- This text fixture also captures the callback function for the generate path service so it can be executed later
- For this test the occupancy map has already been set via the test fixture
- The generate path callback can now be tested by executing the callback function directly
Testing with DI

Here is the code testing the generate path lambda function
This test fixture calls the callback function for the set occupancy map service when a mock function is executed
This test fixture also captures the callback function for the generate path service so it can be executed later
For this test the occupancy map has already been set via the test fixture
The generate path callback can now be tested by executing the callback function directly

There was no invocation of the middleware using DI and all code is testable without invoking the ROS 2 API!
Conclusion
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- Prioritize using pure functions - easier to test and reason about
- Using higher order functions increased the modularity of the code, in this case allowing for different path generating algorithms to be used
- Monadic error handling led to easier error checking
- Refactoring PathGenerator using DI in conjunction with the functional programming paradigm led to code that has 100% coverage
Thanks to:

- Mariyum Gill
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Leveraging a Functional Approach for More Testable and Maintainable ROS 2 Code

Thank you!

All code and the full presentation are available at: